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ON CONTACT PHENOMENA BETWEEN GNEISS AND LIMESTONE IN WESTERN MASSACHUSETTS

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INTRODUCTION

The eastern part of Berkshire County in western Massachusetts is underlain by a vast area of granitic gneiss, known as the *Becket granite gneiss*.[1]

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[1] B. K. Emerson, "Geology of Massachusetts and Rhode Island," *U.S. Geol. Surv., Bull. 597* (1917).

In older papers by the same author, "Geology of Old Hampshire County, Mass.," *U.S. Geol. Surv., Mon. 29* (1898), and "The Geology of Eastern Berkshire County, Mass.," *U.S. Geol. Surv., Bull. 159* (1899), this granite gneiss is designated in part as "Becket conglomerate gneiss" and in part as "Tyringham gneiss."

This gneiss has been regarded as of pre-Cambrian age and the Cambrian and Ordovician rocks that bound it on the west and the east have been thought to lie unconformably upon it.

On its western side, in the Housatonic Valley, the main rock is limestone, called *Stockbridge limestone*, interbedded with quartzite and slate, while on the eastern side there is an area of highly metamorphic schists.

Within the area of the Becket gneiss there are several vertical layers (up to six hundred feet broad) of limestone, which is older than the gneiss. The most important of them, according to Emerson, are situated at Coles Brook in Middlefield, north of Becket Station in Becket, in Washington and Peru, in Hinsdale, and in the valleys of East Lee, Tyringham, and Otis. All the limestone formations within the Becket gneiss area are called *Coles Brook limestone* from the type occurrence at Coles Brook in the northeastern part of the mass. A striking topographical feature of these occurrences of limestone is that they occupy long, narrow valleys in the gneiss highland.

Near the contacts with this limestone the Becket gneiss shows two kinds of endomorphic contact phenomena: In many cases the boundary type of gneiss grows more basic and is called *Lee quartz diorite*. But in other places, the boundary type of gneiss is rich in salic minerals and contains monoclinic pyroxene and titanite. It is called by Emerson "*titanite-diopside diorite aplite*," and is supposed by him to represent a product of assimilation of the limestone by an igneous magma.

During a trip to western Massachusetts in July, 1921, the present writer, together with Dr. N. L. Bowen, had the opportunity of studying outcrops and collecting samples of these contact rocks around Benson Pond east of Washington Station, on the railroad line between Washington and Becket stations, north of Becket Station and in the valley of Goose Pond Brook near East Lee.

As the problem concerning the assimilation of limestone by igneous magmas is now being much discussed, this very instructive case may be of some interest to petrologists. A brief note of field observations and of a microscopic study of the materials collected is therefore given in the present paper together with a discussion of the results.

Numerous questions as to why and how the contact rocks have obtained their present characters arise from such studies, but to many of them no definite answers are yet possible. It often seems wiser to direct our efforts toward finding a sound form of the question, according to Bacon's advice: "Bene interrogatum quasi dimidium responsi." These questions, one may hope, will be cleared up either by future experimental investigation or by accumulating more evidence from natural rocks.

The questions to be discussed in the present paper are: Why is limestone sometimes assimilated by magmas, and sometimes not? What are the factors controlling the formation of silicate minerals in limestone during metamorphism? What laws control the distribution of elements, such as Mg and Fe, which replace each other in solid solutions, among different mineral groups, pyroxenes, amphiboles, and micas, in silicate rocks?

I wish to express my best thanks to Dr. N. L. Bowen for pleasant companionship during the excursions and for many discussions, and especially for his trouble in making the necessary grammatical corrections in my writing.

This work has been carried out with pecuniary assistance from the Geophysical Laboratory of the Carnegie Institution of Washington and from two funds for the advancement of scientific research in my native country, Finland, namely, Alfred Kordelin's General Trust for the Advancement of Progress and Knowledge, and Herman Rosenberg's Travelling Bursaries Trust of the University of Helsingfors.

BECKET GRANITE GNEISS

Emerson[1] gives the following description of the Becket granite gneiss:

> It is a medium to fine grained light-colored biotite (or biotite-muscovite) microcline-oligoclase gneiss, with microscopic epidote uniformly blended with the scanty biotite, and the microcline grains commonly grouped as if made of the crushed fragments of larger porphyritic crystals. There are small areas of light-colored porphyritic granite from which the prevalent rock could have been produced by crushing. A micrographic texture is common. Over large

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[1] *U.S. Geol. Surv., Bull. 597*, p. 154.

areas the dark constituent is in whole or part magnetite in small octahedra. . . . . At its contact with the graphitic rocks the rock is commonly graphitic, and against the limestone it contains in many places secondary calcite grains and tremolite or actinolite.

The following chemical analyses of the Becket gneiss and a related gneiss have been published:[1]

I. Gneissoid granite, Alderman's quarry, Becket, Toscanose-lassenose. Analysis by G. Steiger. Specimen in Petrographic Reference Collection of U.S.G.S. No. 1649.

II. Granite gneiss, Hoosac Mountain. Toscanose. Analysis by E. T. Allen. Specimen *P.R.C.* 1718. Collected by J. E. Wolff. Consists of quartz, microcline, albite, muscovite, biotite, magnetite, titanite, epidote, apatite, zircon.

III. Composite sample of Becket gneiss from 33 localities in the Sheffield quadrangle. Collected by Joseph Barrell and analyzed by R. C. Wells.

	I	II	III
SiO_2	70.62	67.12	68.56
Al_2O_3	15.31	14.97	14.53
Fe_2O_3	1.06	2.61	1.41
FeO	0.43	2.19	2.91
MgO	0.29	0.54	0.60
CaO	1.30	1.69	2.69
Na_2O	4.55	3.92	3.58
K_2O	4.01	5.15	3.62
H_2O-	0.16	0.19	0.06
H_2O+	0.72	1.13	0.97
TiO_2	0.29	0.37	0.55
CO_2	0.88	....	trace
P_2O_5	0.07	0.14	0.17 ZrO_2 0.02
MnO	....	0.02	0.03 S 0.03
BaO	....	0.19 ZrO_2 0.03	0.07 F 0.02
	99.69	100.26	99.82

Through the courtesy of Dr. E. S. Larsen of the United States Geological Survey, I had the opportunity of studying the original specimen of Analysis I, the Becket gneiss from Alderman's quarry. It is a light gray granite, rich in muscovite. All its minerals are clear and unaltered.

In the plagioclase were determined $\beta_D = 1.5345 \pm 0.001$; $\alpha'_D = 1.532 \pm 0.002$; $\gamma'_D = 1.540 \pm 0.002$,[2] corresponding to Ab_{92}.

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[1] F. W. Clarke, *U.S. Geol. Surv., Bull. 591*, pp. 33-34.

[2] The composition of the plagioclases, in this study, was ascertained mainly from the indices of refraction determined in rock powder by the immersion method, using

The *microcline* is finely cross-hatched. The feldspars and the *quartz* form the aplitic mass in which scales of *muscovite*, *biotite*, and *calcite* are scattered.

In the muscovite, $\beta_D = 1.615 \pm 0.003$, and in the biotite $\beta_D = \gamma_D = 1.650 \pm 0.003$. Unfortunately there are not yet sufficient data to establish the composition of the micas from the refractive indices. The biotite probably has about 80 per cent of the iron compound.[1]

The mode of this rock was calculated with the following result:

Quartz	27.7	Biotite	4.0
Albite	38.2	Calcite	2.0
Anorthite	3.2	Apatite	0.2
Microcline	15.0		
Muscovite	10.0		100.3

This is a rock in which calcite occurs as a primary mineral. Emerson remarks (*op. cit.*, p. 153): "Because of its proximity to the Coles Brook limestone it contains microscopic grains of calcite."

All the analyses of the Becket gneiss show an ordinary granitic composition with about equal amounts of potash and soda and very little lime. A study of thin sections of a number of specimens proved this to be a general rule. Some of them, however, do not contain any potash feldspar, but all are rich in mica.

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a monochromatic illuminator and Dr. Merwin's dispersion diagram for the set of liquids (see E. Posnjak and H. E. Merwin, *Jour. Amer. Chem. Soc.*, Oct., 1922). In the case of feldspars, where birefringence is low and dispersion sufficiently known, this method offers the advantage that all the indices of refraction can be determined with only one liquid. In the actual work it was found convenient either to determine β only, or to seek grains showing the highest birefringence and determine, in three of four grains, α' and γ', taking the lowest and highest values found. The composition was then located on the curves published by F. E. Wright, *Am. Jour. Sci.* (4) (1913), pp. 36, 540. The latter is the quickest way and sufficiently accurate to give the composition of the plagioclase within the limits of 2 or 3 mol. per cent.

[1] The lowest indices of refraction in biotites recorded are those in yellowish brown biotite from Vesuvius, $\alpha_D = 1.5412$; $\gamma_D = 1.5745$, and the highest those in black biotite from Somma: $\alpha_D = 1.5795$; $\gamma_D = 1.638(3)$. The highest value of γ is much lower than that often found during this work. The maximum value, found in a biotite from biotite gneiss, railroad line between Becket and Washington, was $\gamma_D = 1.660 \pm 0.003$. Taking this value and $\gamma_D = 1.574$ as limits a very rough approximate estimation of the composition of biotites may be obtained graphically.

LIMESTONE AND SKARN[1]

Emerson characterizes the Coles Brook limestone in the following words:[2] "The Coles Brook is a coarse, highly crystalline, magnesian limestone, locally white and pure, generally graphitic and greatly changed to a mass of silicates—chondrodite, wollastonite,[3] wernerite, hypersthene, pyroxene, amphibole, titanite, adularia, pericline, and others. . . . ."

In the following are given the writer's observations on the limestones in western Massachusetts.

About ½ mile east of *Benson Pond*, 1 mile east of Washington Station, a band of limestone, a few meters broad, occurs in the gneiss. It is rendered impure by the presence of greenish white mica, reddish brown chondrodite, and clear brown titanite.

The *mica* is nearly, though not quite, uniaxial and has $\beta_D = \gamma_D = 1.576 \pm 0.002$. It is a magnesian mica, very poor in iron, but probably not phlogopite.

The *chondrodite* is notably pleochroic, α and β reddish brown, γ pale brown. $\alpha \wedge \beta = 31° \cdot \alpha_D = 1.621 \pm 0.003$; $\beta_D = 1.632 \pm 0.001$; $\gamma_D = 1.655 \pm 0.003$.

This limestone is a calcite rock and contains no dolomite.

In apparent connection with the limestone, on its continuation along the strike, were found many inclusions of clinopyroxene skarn in an aplitic variety of the gneiss which contains varying amounts of the same kind of pyroxene (Fig. 1) as the skarn.

Many of the inclusions are sharply defined, coarsely crystalline masses of grayish green clinopyroxene, although narrow veinlets always protrude into them from the aplite. These veinlets always contain minute grains of red *grossularite-andradite* which is also concentrated within a narrow zone around the inclusions. It is apparently heterogeneous, its index of refraction (n_D) varying from 1.775 ± 0.005 to 1.801 ± 0.005. This means a variation in composition from 25 to 43 wt. per cent andradite in the mixcrystals, supposing them to contain only andradite and grossularite.[1]

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[1] "Skarn.—An old Swedish mining term for the silicate gangue (amphibole, pyroxene, garnet, etc.) of certain iron ore and sulphide deposits of Archaean age, particularly those which have replaced limestone and dolomite. The term is used in this sense by Fennoscandian geologists, but it has been extended to cover analogous products of contact metamorphism in younger formations." A. Holmes, *The Nomenclature of Petrology* (London, 1920), p. 211.

[2] B. K. Emerson, *U.S. Geol. Surv.*, *Bull. 597*, p. 21.

[3] This statement about wollastonite does not occur in the other more detailed reports and may be erroneous.

The *clinopyroxene* has $\beta_D = 1.696\pm 0.001$ and the angle $\overset{|}{c}\wedge\gamma = 43°$. Hence its composition should be $Di_{69}He_{31}$.[2]

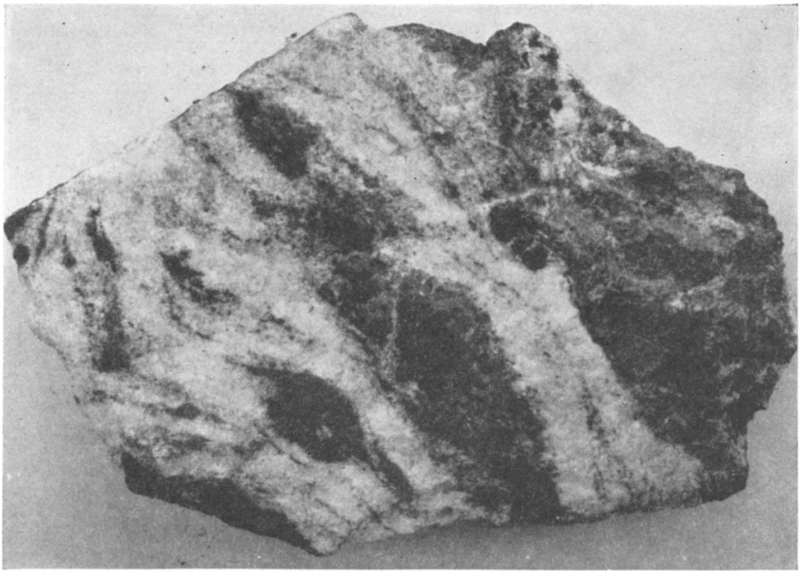

FIG. 1.—Inclusions of clinopyroxene skarn in aplitic gneiss. E. of Benson Pond, Washington, Massachusetts. Eight-ninths natural size.

Together with the garnet in the veinlets there is *quartz*, *microcline* and *plagioclase*. The latter, having $\alpha'_D = 1.532$ and $\gamma'_D = 1.540$, has the composition about Ab_{91}.

[1] W. E. Ford, *Amer. Jour. Sci.* (4), Vol. XL (1915), pp. 33–49.

[2] The determinations of pyroxenes of the diopside-hedenbergite series by means of the indices of refraction were made with a diagram (Fig. 2) based on the optical data given by Wülfing (H. Rosenbusch and E. A. Wülfing, *Mikroskopische Physiographie*, I, 2, p. 203) and on the analyses of the same pyroxenes published by G. Flink (*Zs. Kr.*, Vol. II (1895), p. 585). Although the analyses are antiquated, these data no doubt give a correct idea of the relations between composition and optical properties of clinopyroxenes containing little or no sesquioxydes. Drs. H. E. Merwin and H. S. Washington are at present carrying on an investigation of all the pyroxenes and they no doubt will give a better diagram of this series. As their work is not far advanced and it may be some years before their results are published, we give here the diagram based on Flink's and Wülfing's data.

Small amounts of deep green *hornblende* ($\beta_D = 1.677 \pm 0.002$) are associated with the pyroxene.

Considerable quantities of *epidote* occur near the margins of the skarn inclusions. Its refringence varies within single grains, being lowest in the centers.

On the hillside just *north of Becket Station* there is exposed a vertical layer of limestone, surrounded by clinopyroxene gneiss.

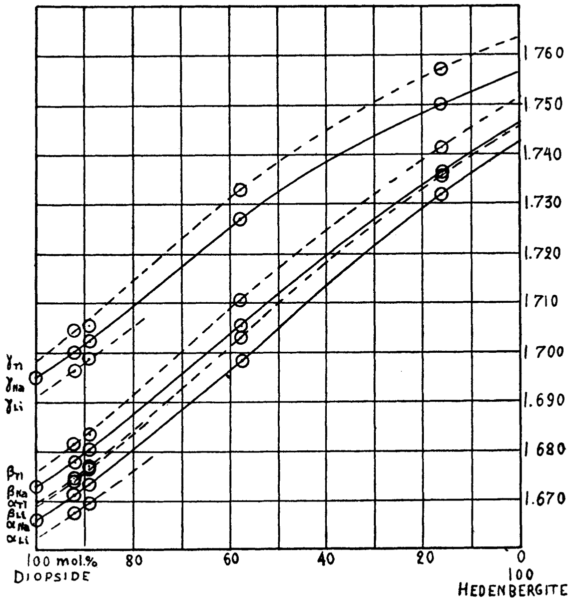

Fig. 2.—Variation of the indices of refraction in the diopside-hedenbergite series. The small amounts of ferric oxide present have been calculated as ferrous oxide. After E. A. Wülfing and G. Flink. The indices of pure diopside were determined by H. E. Merwin.

A specimen of the limestone was found to contain, besides calcite, much quartz and clinopyroxene of the composition $Di_{67}He_{33}$, having $\beta_D = 1.698 \pm 0.002$.

One of those narrow valleys within the Becket gneiss area that are underlain by the Coles Brook limestone is *Goose Pond Brook Valley*. It joins the broader East Lee Valley near East Lee. Limestone occurs in small outcrops in the bed of the brook, and little can be said about its mode of occurrence, but it seems to be in immediate contact with the clinopyroxene gneiss that is exposed close by.

Among the specimens collected some were very rich in *calcite* with only sparing amounts of *dolomite* crystals, the latter being easily recognizable from their higher indices of refraction ($\omega_D = 1.683 - 1.684$; the calcite always was found to have $\omega_D = 1.660$).

Other specimens collected contain pale brown *biotite*, having $\beta_D = \gamma_D = 1.599 - 1.600$, and *quartz*, as rounded grains.

A specimen from the wider *East Lee Valley*, where the Coles Brook limestone occurs as a larger mass, represents a dolomite-rock containing rounded grains of *quartz* and *microcline*, and minute crystals of *pyrite* and scales of brownish, nearly uniaxial *mica* with $\beta_D = \gamma_D = 1.599 \pm 0.002$.

It may be mentioned that these characters are the same as those in the most common types of the Stockbridge limestone in the Housatonic Valley. Analyses[1] of the Stockbridge indicate that there are all variations between dolomite-rocks and calcite-rocks represented. We collected specimens of this limestone from Glendale quarry. It is a dolomite-rock, with much fine scaly brownish *mica* ($\beta_D = \gamma_D = 1.584 \pm 0.002$) and brown *tourmaline* ($\omega_D = 1.639 \pm 0.001$).

BANDED GNEISS NEAR THE LIMESTONE AND THE VARIATION OF ITS MINERAL COMPOSITION

The gneiss, near the vertical, or almost vertical, layers of limestone, always shows a banded structure parallel to the strike of the limestone. At the immediate contacts it is clinopyroxene gneiss. Farther away there are various bands, some containing hornblende, and others with almandite, biotite or magnetite as the principal mafic minerals, and among them are bands of the clinopyroxene gneiss also.

The individual bands may be homogeneous or banded in detail (Fig. 3), due to the unequal distribution of the minerals. The breadth of homogeneous bands varies from less than one meter to a hundred meters. Among the pyroxene-bearing bands, however, none was found thicker than some ten meters.

A common feature of all the varieties of gneiss, of widely different mineral composition, is the presence of very albitic plagioclase (mostly about 90 per cent Ab) and epidote whose amount increases with the quantity of the femic compounds, a fact indicating that it is a substitute for anorthite. The epidote occurs as clear, individual crystals, often intergrown with quartz in the myrmekite fashion.

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[1] B. K. Emerson, *U.S. Geol. Surv., Bull. 159* (1899), pp. 87 and 99.

Another feature significant in connection with the conditions of formation of these banded gneisses is the absence of perthitic threads of plagioclase in the microcline, which is clear and finely cross-hatched. The texture, on the whole, is aplitic, and all the main minerals are equally xenomorphic.

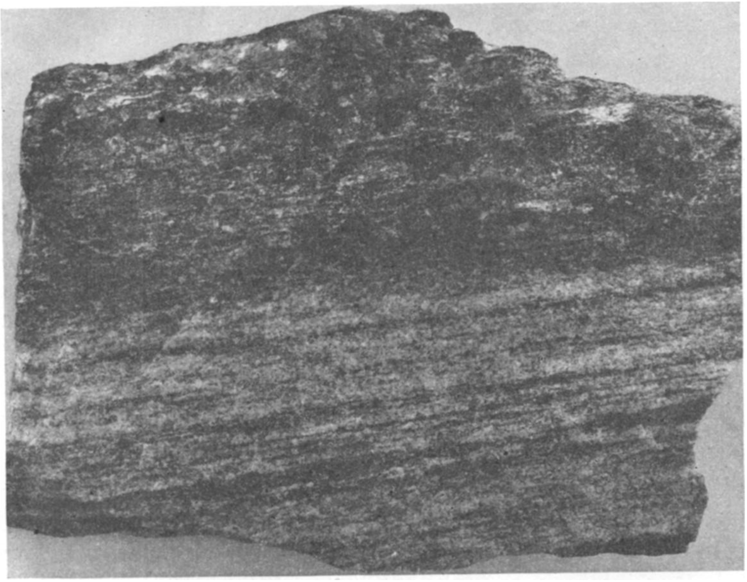

Fig. 3.—Banded clinopyroxene gneiss. W. of Benson Pond, Washington, Massachusetts. Eight-ninths natural size.

Emerson (*op. cit.*, p. 153) published an analysis of clinopyroxene gneiss, called by him "titanite-pyroxene diorite aplite," from "east of C. Conwell's place, South Peru, Mass." The analysis, made by W. T. Schaller, is quoted below (p. 275).

I have found these clinopyroxene-bearing rocks to be exceedingly variable in composition, and the analysis has happened to be made on a rather exceptional type. Most specimens collected by us from the same tract and, also, one collected by Professor Emerson from the Peru line, "the same ledge as the rock analyzed" (*U.S.*

Geol. Surv., P.R.C. 1715), contain considerable amounts of quartz and microcline. They therefore must have a higher percentage of silica and potash. Assuming the plagioclase to contain 90 mol. per cent Ab and a notable quantity of epidote to be present, the mode given in the table was calculated from the rock analysis by the writer. The pyroxene was computed as a diopside-hedenbergite with 10 per cent (Mg, Fe)SiO_3 and 4 per cent Al_2O_3.

The clinopyroxene, in the specimen from the Peru line, is pale green without any notable pleochroism. It was found to have $\alpha_D = 1.695 \pm 0.002$, $\beta_D = 1.706 \pm 0.002$; $\gamma_D = 1.724 \pm 0.002$, and should therefore contain 60 mol. per cent diopside and 40 per cent hedenbergite, or $Di_{60}He_{40}$, while calculation from the analysis gave $Di_{48}He_{42}$. Thus the specimen analyzed contained a pyroxene richer in iron. As we shall see, the composition of the clinopyroxene in these gneisses varies markedly from place to place.

	Per Cent	Mol.
SiO_2	60.44	1.007
Al_2O_3	16.26	159
Fe_2O_3	0.07	.....
FeO	3.52	49
MgO	1.75	44
CaO	7.86	140
Na_2O	7.13	115
K_2O	0.44	5
H_2O+	0.38	.....
H_2O-	0.29	.....
TiO_2	1.33	16
P_2O_5	0.58	4
MnO	0.06	1
ZrO_2	0.06	.....
FeS_2	0.10	.....
	100.27	

Mode			
Albite		60.26	
Anorthite		7.51	
Potash feldspar		2.78	
Pyroxene	$CaSiO_3$	8.82	20.49
	$MgSiO_3$	4.40	
	$FeSiO_3$	6.47	
	Al_2O_3	0.80	
Epidote		1.93	
Quartz		2.16	
Titanite		3.14	
Apatite		1.34	
Zircon		0.09	
Pyrite		0.10	
		99.80	

The epidote is highly birefracting and has $\beta_D = 1.750 \pm 0.003$, nearly the same value as that found in the epidote from Knappenvand, Sulzbachtal,[1] which contains 33 per cent of the ferric epidote (16 per cent Fe_2O_3) and has $\beta_D = 1.7540$.

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[1] M. Goldschlag, *Tscherm. Min. Petr. Mitt.*, Vol. XXXVIII (1917), p. 23. The data given in this study, the most careful one ever carried out on the epidote group, are not yet consistent enough to allow the determination of the amounts of the aluminous and the ferric compounds in epidotes more accurately than with a possible error of ±5 per cent.

The prominent characters of the mineral composition of the various kind of gneiss are stated in the following. The mineral constituents of each rock are named in the approximate order of abundance. The refractive indices were determined, if not stated otherwise, with a maximum error of ±0.003 in biotite and hornblende and epidote, and ±0.002 in plagioclase and pyroxene. The composition of the minerals is given in terms of mol. per cent, stating: in plagioclases the percentage of anorthite (An), in clinopyroxenes (diopside-hedenbergite) the percentage of hedenbergite (He), in hornblende the total Fe as a percentage of Fe+Mg,[1] and in the biotites and epidotes (very roughly) the percentages of their iron compounds.

Aplitic clinopyroxene gneiss around the inclusions of skarn. Mainly microcline, subordinate plagioclase (An_8), quartz, clinopyroxene ($\beta_D = 1.705$, $\gamma_D = 1.727$, He_{42}), epidote, variable, sometimes very poor in Fe,[2] calcite.

Banded clinopyroxene gneiss (Fig. 3) in biotite gneiss, W. of Benson Pond. Microcline, quartz, plagioclase ($\alpha'_D < 1.536$; $\gamma'_D = 1.544$; An_{15}), clinopyroxene (He_{69}),[3] titanite, epidote.

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[1] Calculated from the diagrams given by W. E. Ford, *Amer. Jour. Sci.*, Vol. XXXVII (1914), p. 185.

[2] I measured in one case for different wave-lengths, with a maximum error ±0.001:

	α	β	γ
Tl..........	1.703	....	1.707
D..........	1.698	1.700	1.702
C..........	1.693	....	1.697

These values are lower than any given in the literature (cf. M. Goldschlag, *loc. cit.*). This mineral is, however, monoclinic, and not a zoisite. 2V=90° appr.

[3] In it were determined, with a maximum error ±0.001:

	α	β	γ
Tl..........	1.724	1.7305	1.748
D..........	1.720	1.726	1.743
C..........	1.716	1.721	1.738

The birefringence suggested that this clinopyroxene is richer in hedenbergite than any other found in this tract. Its refractive indices for various wave-lengths are in fair agreement with those of $Di_{31}He_{69}$ as shown on the diagram. Its extinction

"Pyroxene-titanite aplite" from the Peru line. Plagioclase ($\beta_D = 1.536$; $\alpha'_D = 1.531$; $\gamma'_D = 1.542$; An_{10}), microcline, quartz, hornblende ($\beta_D = 1.676$; Fe_{51}), clinopyroxene ($\alpha_D = 1.695$; $\beta_D = 1.706$; $\gamma_D = 1.724$; He_{40}), titanite, biotite ($\beta_D = \gamma_D = 1.647$; 80 per cent Fe-comp.), epidote ($\beta_D = 1.750$; 33 per cent Fe-comp.), apatite.

Intrusive layer in limestone N. of Becket Station. Quartz, plagioclase (An_{11}), microcline, clinopyroxene ($\beta_D = 1.700$; He_{35}), hornblende ($\beta_D = 1.680$; Fe_{53}), grossularite-andradite ($n_D = 1.80$; 40 wt. per cent andradite), calcite, epidote.

Band in the gneiss, railroad cut W. of Becket Station. Quartz, microcline, clinopyroxene (colorless; $\alpha_D = 1.685$; $\beta_D = 1.690$; $\gamma_D = 1.714$; $\gamma \wedge \dot{c} = 41°$; He_{25}), actinolite (pale green; $\beta_D = 1.638$; Fe_{19}), graphite, calcite, titanite.

Clinopyroxene gneiss near limestone in the valley of Goose Pond Brook. Clinopyroxene (colorless, $\beta_D = 1.681 \pm 0.001$; He_{11}), amphibole ($\beta_D = 1.633 \pm 0.002$; Fe_{14}), quartz, microcline, plagioclase ($\beta_D = 1.534$; An_7), epidote ($\beta_D = 1.730$; 18 per cent Fe-comp. or 9 wt. per cent Fe_2O_3). Occasional scapolite ($\omega_D = 1.572 \pm 0.001$; $\epsilon_D = 1.547 \pm 0.001$; about $Me_{50}Ma_{50}$) and black tourmaline.

Dark band in the gneiss South of Benson Pond. Clinopyroxene ($\beta_D = 1.695$; He_{31}), hornblende ($\alpha_D = 1.672$; $\beta_D = 1.685$; $\gamma_D = 1.695$; Fe_{59}), plagioclase (zoned, An_{17} to An_7), quartz, microcline, titanite, biotite ($\beta_D = \gamma_D = 1.635$; about 65 per cent Fe-comp.).

Dark band N. of Benson Pond. Plagioclase (zoned, An_{23} to An_{16}), hornblende ($\beta_D = 1.660$; Fe_{36}), biotite ($\beta_D = \gamma_D$ 1.642; 75 per cent Fe-comp.), quartz, epidote, titanite, apatite.

Dark band in the gneiss N. of Becket Station. Biotite ($\beta_D = \gamma_D = 1.620$; 50 per cent Fe-comp.), hornblende ($\beta_D = 1.650$; Fe_{29}), plagioclase ($\beta_D = 1.536$; $\alpha'_D = 1.532$; $\gamma'_D = 1.541$; An_{10}), microcline, quartz, epidote. The quantity of epidote is considerable.

"Lee quartz diorite" from west end of Goose Pond. Plagioclase (zoned, An_{32} to An_{29}), hornblende ($\beta = 1.665$ appr.; Fe_{40}), cum-

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angle $\gamma \wedge \dot{c}$ however, does not accord with the series, being 58° instead of 46° 20′. Probably this clinopyroxene contains a certain amount of aegirite, although its very faint pleochroism (α = pure green, γ = brownish) indicates that the amount may be small.—In another specimen was found a clinopyroxene He_{60}($\beta_D = 1{,}721$).

mingtonite, forming the inner parts of the aggregates of amphibole (positive, 2V large, $\beta_D = 1.650$; about 40 mol. per cent $FeSiO_3$), quartz, ilmenite, apatite, zircon.

Almandite amphibolite, band in gneiss, roadside W. of Benson Pond. Plagioclase ($\alpha'_D = 1.540$; $\gamma'_D = 1.548$; An_{25}), almandite ($n_D = 1.806 \pm 0.001$; probable composition[1] 70 mol. per cent almandite, 15 mol. per cent pyrope and 15 mol. per cent grossularite), hornblende ($\beta_D = 1.665$; Fe_{40}) microcline, biotite ($\beta = \gamma = 1.648$; about 80 per cent Fe-compound), ilmenite, apatite.

Biotite gneiss, railroad line between Washington and Becket stations. Quartz, plagioclase (An_9) microcline, biotite ($\beta_D = \gamma_D = 1.660$, chiefly iron compound), hornblende ($\alpha_D = 1.697$; $\beta_D = 1.708$; $\gamma_D = 1.709$;[2] $2V\alpha$ small Fe_{90}), magnetite, epidote ($\alpha_D = 1.741 \pm 0.002$; $\beta_D = 1.760 \pm 0.005$; $2V = 75°$ appr.; about 35 mol. per cent iron comp.).

THE MG:FE PROPORTION IN THE VARIOUS BANDS OF THE GNEISS AND IN ITS DIFFERENT MAFIC MINERALS

A comparison of the Fe:Mg proportions, as determined from the refractive indices of the pyroxenes, amphiboles, and biotites in the various kinds of gneiss, shows at once that they are controlled by definite laws. For the sake of convenience, the values of the atomic portions of Fe as a percentage of Fe+Mg (briefly called the Fe-quotient) are tabulated (p. 279).

In this table, the rocks are arranged in the order of decreasing Fe-quotient in their amphiboles and pyroxenes. Now, comparing this order with the statements of the approximate quantitative proportions of the minerals given in the preceding chapter, we find at once that it is, also, at least nearly the order of increasing basicity or decreasing acidity, excepting, however, the two last-named examples of clinopyroxene gneiss. Their case will be discussed below.

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[1] P. Eskola, "On the Eclogites of Norway," *Videnskapsselsk. Skri. Mat.-naturv. Kl.* I, No. 8 (1922), p. 9.

[2] The indices match the highest values represented in the amphiboles studied by Ford (*Amer. Jour. Sci.*, Vol. XXXVII [1914], p. 181), i.e., those of the hornblende from Cornwall, Orange County, New York, which has a mean index 1.71 and contains 23.35 per cent FeO and 7.41 per cent Fe_2O_3 against 1.90 per cent MgO and 12.10 per cent Al_2O_3.

In other words: the larger the quantity of the mafic minerals, the smaller is their Fe-quotient. In the most acid types of gneiss, rich in quartz, we find biotite and hornblende, and often clinopyroxene also, extremely rich in iron. In the mafic minerals of the "dark bands" the amount of iron in proportion to magnesia is much less.

At the same time as the Fe-quotient decreases, the amount of anorthite in the plagioclases increases. This relation is somewhat obscured by the epidote, a substitute for the anorthite.

ROCKS	100 FE : (FE+MG) IN			OTHER MINERALS
	Clinopyroxenes	Hornblendes	Biotites	
Biotite gneiss, railroad at Becket Station	......	90	95(?)	......
Clinopyroxene gneiss, W. of Benson Pond	69	......	......	......
Clinopyroxene gneiss, "the Peru line"	40	51	80	......
Clinopyroxene gneiss, Becket Station	35	53	......	Grossularite-andradite, 40 per cent andr.
Dark band in gneiss, S. of Benson Pond	31	59	65	......
Almandite amphibolite, W. of Benson Pond	......	40	80	Garnet with 70 per cent almandite
Dark band in gneiss, N. of Benson Pond	......	36	75	......
Dark band in gneiss, Becket Station	......	29	50	......
Clinopyroxene gneiss, railroad between Becket and Washington	25	19	......	......
Clinopyroxene gneiss, Goose Pond Brook	11	14	......	......

The percentage of the iron compound in the epidotes does not show quite regular relations with that in the mafic minerals. This is probably connected with the later origin of the epidote.

This correspondence between the Fe:Mg ratio and the relative proportion of salic and femic minerals is a special case of what is inherent in any cognate series of igneous rocks which have been derived from a common magma by the processes known as magmatic differentiation. Its occurrence in the banded gneiss proves that the band structure is in itself a product of differentiation. In other words, the "dark bands" are those in which the minerals containing solid solutions are richest in the highest melting compounds or, more exactly, compounds least soluble in the residual magmas. The mafic minerals of these most "basic" members of the series are pyroxene and amphibole. With increasing acidity biotite and muscovite appear successively.

The occurrence and composition of clinopyroxene does not always follow this rule, and for a very obvious reason: its occurrence is due to the assimilation of limestone, which is dolomitic, and low in iron. Therefore, when it reacts with the highly siliceous gneiss magma, there is formed pyroxene and, also, hornblende and biotite, low in iron, provided differentiation by crystallization has not changed the composition of the magma after assimilation. In many cases a differentiation happened, however, and therefore the mafic minerals of very acid clinopyroxene gneisses not immediately connected with limestone usually show a high Fe-quotient.

Another interesting question is this: How are magnesia and the iron oxides distributed between the different ferromagnesian minerals?

As appears from the table on page 279, there are definite relations between the pyroxenes, amphiboles, and biotites, in this respect. Biotite is regularly the richest in iron and clinopyroxene the poorest. The figures do not show any constant relations between the Fe-quotients, however. This is only what may be expected. From theoretical considerations the distribution of elements in different isomorphous series in a rock is evidently a very complicated process, depending upon the composition of the solutions from which the minerals crystallized and, also, on the temperature and pressure conditions during crystallization. In rocks of identical bulk composition these relations may be expected to vary with the physical conditions. It may be hoped that, when once they are better understood, we shall be able to draw from them certain conclusions as to the conditions under which the rocks originated.

The present writer has formerly studied the almandite-pyrope garnets of different rocks from this standpoint and has arrived at the conclusion that, in rocks of similar composition, those formed under highest pressures have garnets richest in the magnesia compound.[1]

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[1] P. Eskola, "The Mineral Facies of Rocks," *Norsk geologisk Tidskrift*, Vol. VI (1920), p. 172.

These brief statements are given here in order to call the petrologist's attention to these relations, formerly very little studied.

VARIATION OF MINERAL PARAGENESIS IN METAMORPHIC LIMESTONE

Sedimentary limestones generally consist of carbonates of calcium and magnesium, and of silica, in the form of quartz. Very often they also bear clayey materials, containing alumina, iron oxides, potash, etc. When such material is brought from surface conditions down to deeper levels where a higher temperature prevails there will occur reactions of the general type:

$$RCO_3+SiO_2=RSiO_3+CO_2.$$

The temperature limit above which the right-hand side of the foregoing equation represents the stable combination, or the transformation point of the chemical system, is raised with pressure. For the reaction $CaCO_3+SiO_2=CaSiO_3+CO_2$, V. M. Goldschmidt calculated the approximate equilibrium curve on the basis of Nernst's affinity theorem.[1] According to this curve, the equilibrium temperature increases rapidly with the pressure, being 850° at 300 atm. Thereafter the rise of the equilibrium temperature with pressure should be nearly linear and so slow that as much as 15,000 atm. would be needed at 950°. Considering rocks of neighboring occurrences which have originated under similar pressures but at different temperatures, as is often the case at the contacts of igneous masses, the limestone indicates what parts of it have been heated above the reaction point. If the pressure be known, the temperature may be estimated in degrees. In the case of rocks whose metamorphism has taken place under pressures of more than 3,000 atm., or at depths of more than 10 kilometers, the equilibrium temperature is but slightly variable with pressure, and the mineral composition of silica-bearing limestones is mainly an indicator of temperature, or the limestone may be used as a *geologic thermometer.*

This curve is not claimed to be more than approximate. Experimental investigation may give considerably different results.

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[1] V. M. Goldschmidt, "Die Gesetze der Gesteinsmetamorphose," *Vid. selsk. Skr. Mat.-naturv. Kl.*, No. 22 (1912).

Certain facts known at present would seem to indicate that the curve may lie at somewhat lower temperatures. Its general character, however, agrees well with petrological experience and is not likely to be subject to any great changes.

From the standpoint of the phase-rule, a mixture of calcium carbonate and silica is a three-component system and therefore can have a maximum of three phases in coexistence under variable pressure and temperature conditions, that is, in a divariant system. Below the transformation curve the possible three-phase combinations are either silica, calcite, and carbon dioxide or silica, calcite, and wollastonite. Above the curve we may have either wollastonite, carbon dioxide, and calcite or wollastonite, carbon dioxide, and quartz (or any other form of silica).

Thus wollastonite may be stable and even be formed at temperatures below the transformation curve, but only if silica meets lime in other form than carbonate and no free carbon dioxide is present. The occurrence of wollastonite, therefore, is not in itself a sufficient evidence that the rock had been heated above the transformation temperature. On the other hand the occurrence of both quartz and calcite proves conclusively that it never has.

The temperature of transformation may be considerably depressed if the partial pressure of carbon dioxide is kept low as a result of its continual removal, e.g., by circulating solutions. This case may occur in the formation of metasomatic ore deposits, and in fissure veins. The conditions are here complicated also because the addition of substances and formation of minerals may have continued at different temperatures. As a matter of fact, observation usually indicates a definite sequence of formation of minerals in such deposits.

While, then, many complications are to be expected where circulating solutions have been prominent agents, we may still use limestone as a geologic thermometer with considerable confidence in those cases in which quartz or the silicates occur evenly distributed as true rock constituents.

As we are concerned, in natural rocks, with calcium and magnesium carbonates, the resulting silicates will be those of calcium and magnesium, or double compounds of both. It is to be expected that magnesium-bearing carbonates will react with the silica at lower temperatures than calcium carbonate. Each silicate to be formed may have its own equilibrium curve.

This assumption has been very strongly supported by petrological investigations which I have carried out in the pre-Cambrian limestone of Finland.[1] In the southeastern part of the pre-Cambrian area of Fennoscandia there are extensive formations all of whose characters point toward metamorphism at low temperatures. In the limestones of this area, quartz occurs together with dolomite, and fine scaly micaceous minerals (biotites rich in magnesia) are usually the only silicates. Sometimes epidote occurs, a fact indicating that this hydrated calcium aluminium silicate also belongs to the low temperature minerals.

Northwest of this low temperature area there is a broad zone within which the limestones contain, besides mica, amphiboles of the tremolite-actinolite series, but no other silicates. Going farther northwest diopside-hedenbergite is added to the list of minerals of the metamorphic limestones, together with many others, such as scapolite, vesuvianite, and grossularite-andradite. Finally we find, as local developments near the contacts of igneous masses, but never in regional distribution, wollastonite limestone, and in this most of the other silicates may occur also. This mode of occurrence clearly indicates that wollastonite, among the lime-bearing silicates, requires the highest temperature to form.

We may thus discriminate the following four paragenetic types of limestones:

1. **Quartz limestone,** in which quartz is coexistent with the dolomite.
2. **Tremolite limestone.** Tremolite is usually present; quartz occurs in calcite-rock, but is not coexistent with dolomite.
3. **Diopside limestone.** Diopside is usually present, quartz occurs together with calcite but not with dolomite.
4. **Wollastonite limestone.** Wollastonite is present, provided the rock contains silica in excess of the amount needed to form the

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[1] Pentti Eskola, Victor Hackman, Aarne Laitakari ja W. W. Wilkman, Suomen kalkkikivi. With an English summary by P. E., "Limestones in Finland," *Suomen Geologinen Toimisto, Geoteknisiä Tiedonantoja,* No. 21 (1919).

magnesium-bearing silicates. Quartz and calcite do not occur in contact with each other. Instead either of the combinations calcite-wollastonite or wollastonite-quartz occurs.

Actual rocks have commonly been found in fair accordance with these rules of association. As was pointed out above, wollastonite is in itself stable below the transformation temperature of calcite-silica, if there is no free carbon dioxide present. In the same way diopside and tremolite are stable below those temperatures where they may be formed from the carbonates and silica, again provided that there is no carbon dioxide present. Now there actually is no free carbon dioxide after the formation of the silicates, as it is carried away either as gas or in solutions. Therefore, although the reactions are reversible, they are not reversed during the period of gradual cooling when the rocks are brought up toward the earth's surface through the process of denudation. This fact, of course, adds very much to the usefulness of metamorphic limestone as a geologic thermometer. We always read the highest temperature to which it has ever been exposed. It is a maximum thermometer.

The formation of different minerals under different conditions in limestones presents a special case of the more general rules of adjustment of mineral composition in response to the conditions existing. The writer has proposed the term *mineral facies*[1] to designate a group of rocks which have originated under conditions so similar that a definite chemical composition has resulted in the same set of minerals. Applying this principle to various kinds of rocks, we arrive at a natural rock classification in which main divisions are the groups called mineral facies.

The four paragenetic types of limestone may be paralleled with the facies system of the silicate rocks in the following way:

Under conditions similar to those that give rise to quartz limestones, rocks having the bulk composition of gabbros have been metamorphosed into chlorite-epidote-albite rocks. This mineral facies has been called the *greenschist facies.*

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[1] P. Eskola, "The Mineral Facies of Rocks," *Norsk geologisk tidskrift,* Vol. VI (1920), pp. 143–94.

Tremolite limestones correspond with transitional forms between the greenschist facies and another facies called the *amphibolite facies*, because a rock of gabbroid composition whose minerals have formed under the conditions of this facies, appears as a plagioclase-hornblende rock, an amphibolite.

The diopside limestones, so far as known at present, also belong to the amphibolite facies, and even some of the wollastonite limestones belong here, but the last named cover a wide range of temperature and pressure conditions corresponding to several kinds of mineral development in the silicate rocks, and a gabbroid material may give any one of the mineral combinations: plagioclase and clinoenstatite-diopside solid solutions (provisionally referred to as the *sanidinite facies*) or plagioclase, diopside, and hypersthene (*hornfels facies*), or diopside-jadeite solid solutions and pyrope-almandite solid solutions (*eclogite facies*).

Metamorphic limestone as a geologic thermometer can be calibrated against the transformation points of the silica minerals. The fact that quartz, and not tridymite, occurs even with wollastonite, would seem to indicate that the wollastonite-curve passes below the transformation point quartz-tridymite. This is, according to Fenner,[1] 870°, but it must rise somewhat with pressure. As to the transformation point α-β-quartz at 575°, it has been established that crystals of quartz in a diopside limestone from Parainen in southern Finland, have been originally α-quartz,[2] while the quartz-dolomite rocks of eastern Finland contain clear crystals of quartz which is apparently primary β-quartz. More observations on this subject are desirable.

It is to be hoped that the temperature-pressure curves for the different silicate-carbonate equilibria may be determined exactly by experiment, in the near future.

In the contact zones of the Becket gneiss in western Massachusetts three of these paragenetic types of limestone occur, namely: quartz limestone, tremolite limestone, and diopside limestone. The temperature was probably nowhere high enough to allow wollastonite to be formed,[1] and quartz is generally found in contact with calcite.

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[1] C. N. Fenner, *Amer. Jour. Sci.*, Vol. XXXVI (1913), p. 331.

[2] A. Laitakari, *Bull. Com. géol. Finl.*, 54 (1920), p. 40.

Quartz limestone is the most widely distributed type in western Massachusetts. Most of the Stockbridge limestone belongs to it and, also, much of the Coles Brook limestone. Such were the specimens from Goose Pond Creek and East Lee described above (p. 272). They consist of dolomite and quartz, sometimes with microcline.

During the excursions we did not happen to meet with any typical tremolite limestone, but it is apparent from Emerson's descriptions that it is a common type, in the Stockbridge as well as in the Coles Brook.[2]

Tremolite limestone is noted "south of Becket" (Emerson, *U.S. Geol. Surv., Mon. 29*, p. 27), and from Lee (*U.S. Geol. Surv., Bull. 159*, p. 84). Tremolite but no pyroxene in limestone is mentioned in the "Mineral Lexicon of Eastern Berkshire Co." (last-cited volume) from Windsor, Monterey, and the Cobble in Tyringham.

Through the courtesy of Mr. E. V. Shannon the writer was able to study specimens from the collections of the United States National Museum of tremolite limestone (Stockbridge) from Lee, Massachusetts, and from Canaan, Connecticut, near the Massachusetts line. The rock from both localities was found to consist of dolomite, calcite, and tremolite, with some brown mica ($\beta_D = \gamma_D = 1.582 \pm 0.003$), but no quartz. It thus proves to represent a true equilibrium under those temperature-pressure conditions which give rise to tremolite limestone.

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[1] Cf. footnote 1 on p. 285.

[2] It might be objected that it is not justifiable to regard the Stockbridge and the Coles Brook limestones as equivalents in their metamorphic development. For, if the former is Cambrian, while the latter, with the Becket gneiss intrusive in it, is pre-Cambrian, the Stockbridge cannot have been influenced by the heat of this intrusion which undoubtedly has changed the Coles Brook limestone. Now the plain fact is that the same three types of mineral paragenesis occur in both of them. The Coles Brook limestone, when belonging to the quartz type, is exactly like the most common type of Stockbridge limestone. The occurrence of tourmaline in the latter, recorded above, points to the vicinity of magmas. Emerson knew this, and he assumed that there may be post-Cambrian igneous masses not quite exposed on the present land surface. If this is true, then the earlier and the later intrusions have taken place during very similar physical conditions. It seems worth while, in future investigation of the geology of western Massachusetts, to consider the possibility that the Becket gneiss is of post-Cambrian origin, and the Coles Brook limestone only the margin of the Stockbridge. In fact our observations at the eastern as well as at the western contact of the Becket batholith seemed to indicate that this is the case.

Diopside limestone occurs so commonly that it is not necessary to name more than a few localities, as examples. Emerson[1] describes pyroxene- and actinolite-bearing limestone from Hinsdale and East Lee, both being Coles Brook limestone. His "Mineral Lexicon of Eastern Berkshire Co." (*op. cit.*) mentions pyroxene from the Stockbridge limestone from New Marlboro and several places in Tyringham.

The writer studied diopside limestone from Becket Station, a combination of calcite, quartz and diopside. It is a rock of the diopside limestone type. All the dolomite has been exhausted in the formation of diopside, while some quartz has been left.

Theoretical reasoning leads to the conclusion that the quartz-carbonate rocks, when they are metamorphosed under medium temperature conditions, corresponding to the tremolite and diopside limestone types, are likely to become poorer in dolomite. This must finally cause a dedolomitization of the limestone.

The silica need not occur within the limestones themselves, but may react at the boundaries. In small bodies of limestone bounded by highly siliceous rocks, and especially when submerged in magmas of such acid rocks, this may be expected to give rise to a perfect dedolomitization. So far as the writer's experience goes, small bodies of limestone inclosed in granites or gneisses really consist of calcite-rock, while magnesium-bearing silicates occur at their contacts. This rule was confirmed in the Massachusetts localities studied, near Benson Pond and near Becket Station.

ASSIMILATION OF LIMESTONE BY GRANITIC AND PEGMATITIC MAGMAS

The writer believes that the mode of occurrence of the clino-pyroxene gneiss around and near the occurrences of limestone included in the gneiss is in itself sufficient evidence that the gneiss has received its excessive amount of lime through assimilation of the limestone.

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[1] *U.S. Geol. Surv., Bull. 159*, pp. 32 and 51.

We have found that the clinopyroxene gneiss has, in the majority of cases, a composition that is nearly the same as that of the ordinary Becket gneiss of the surrounding area, excepting that it has a higher amount of lime. A bulk composition may therefore be computed from the analysis of the gneiss quoted above (p. 268), by allotting CaO enough to form anorthite with all the excess alumina (actually present in the micas), to form diopside with all the (Mg,Fe)O present, and titanite with all the TiO_2 present. Such a calculation indicates practically no other change in the composition than an increase in the percentage of lime from 1.30 to 2.97 per cent. The rock would contain 25.2 wt. per cent quartz, while the actual Becket gneiss has 27.7 wt. per cent.

The actual clinopyroxene gneiss in many cases differs from this imaginary rock in being poorer in quartz, and having soda in excess over potash or potash over soda. The aplitic gneiss around the skarn inclusions near Benson Pond is an example of a highly potassic type low in soda and silica, being composed practically of potash feldspar only. The analyzed rock from south Peru, on the other hand, is an extremely sodic variety, low in potash and silica. In both cases practically all the excess silica is gone, and the feldspars and the pyroxene only have been left.

Where a magnesic clinopyroxene occurs in an acid gneiss it proves that the assimilation of limestone had happened nearly in place without further development, while the occurrence of pyroxene high in the iron compound, as was found in some cases, indicates that some differentiation had taken place after assimilation. Both cases occur in the banded Becket gneiss (cf. p. 277).

The *skarn* exhibits a special case. It is supposed to be a pneumatolytic contact-product formed in limestone in such a way that adjacent magmas have brought in silica and metal compounds which have replaced the carbonate.

It is pretty clear, in the case of the clinopyroxene gneiss in question, that it has been formed in part by direct assimilation of limestone by the gneiss magma and in part by the assimilation of skarn previously formed by contact action.

The main indication of the banded structure of the gneiss seems to be that its intrusion and crystallization has happened under the conditions of stress and movements. The effective stirring together of the earlier solid materials with the newly intruded mass doubtless was one of the chief reasons why assimilation of limestone on a rather large scale has occurred here.

Very obviously some amount of assimilation of older silicate rocks associated with the limestone has also taken place. Some evidences to this effect have been presented by Emerson.[1] In its actual characters, however, the banded gneiss is altogether an igneous rock and its band structure is not by any means a direct result of injection combined with some kind of ultrametamorphism. Its whole structure is markedly different from that of such injection gneisses and migmatites known to me from many other regions and, also, from the eastern boundary zone of the Becket gneiss west of Chester.

We may make some comparisons with similar phenomena in other regions. Such clinopyroxene gneisses, or clinopyroxene granites, occurring in connection with limestones and evidently formed by assimilation of limestones surely do occur in many tracts. That they are little noticed may in part be due to their inconspicuous aspect and often imperceptible difference in the hand specimen from ordinary granites and gneisses. On the other hand, it is quite certain that they are not by any means regular associates of granites intruding limestones. I shall name some examples from my own experience.

My work in the Orijärvi region in southwestern Finland proved the absence rather than the occurrence of such products of assimilation of limestone, although it is an area where gneissic granites are intrusive into limestone-bearing formations. Only in a few places was the boundary type of the gneiss granite against limestone found to be diopside-bearing,[2] and only where it intersected limestone as dikes. None of the granites designated as "microcline granite," which are distributed all through southern Finland and very often cut limestones or contain inclusions of them, was ever found to contain clinopyroxene as a rock mineral, excepting in pegmatite dikes (cf. below). Similar relations have also been found obtaining in the well-known limestone-bearing area of Parainen (Pargas).[1]

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[1] *U.S. Geol. Surv., Bull. 597*, p. 154.

[2] P. Eskola, *Bull. Comm. géol. Finl.*, No. 40 (1914), p. 61.

Another feature with which the non-occurrence of assimilation is evidently connected is that this granite which forms veined gneisses or migmatites with all kinds of siliceous rocks has never been intruded into limestones to form intimate mixtures. Therefore the writer made the following general statement:[2] "The resistance offered by limestones against granitization is very remarkable. Even in the midst of a migmatite area, where all siliceous rocks have been thoroughly mixed or assimilated with the granite magma, the limestones are generally quite free from granitic injections, and are intersected only by rectilinear dikes." More evidence of assimilation of limestone by granite magma was brought forth during an investigation of certain areas in Transbaikalia.[3]

The peninsula of Sviatoy Noss, on the east coast of Lake Baikal, is made up of crystalline schists, among which are numerous masses of limestones, and of huge batholiths and smaller bodies of granites intrusive into the schists. The granites, when meeting limestone either as dikes or as large masses, show no endomorphic change whatever at the contacts, while in certain intrusive masses there is a very remarkable change in the whole rock bodies, the rocks (called sviatonossite) being composed of alkali feldspars with aegirite-augite and andradite. The high percentage of lime present has clearly been derived from the limestone, but the process of assimilation has taken place in such a way that andradite-clinopyroxene skarn has first been formed from the limestone and the skarn has subsequently been absorbed. This is evident from the common occurrence of fragments of skarn in the rock showing every degree of assimilation. Finally, all the minerals have crystallized out from the magma and the rock is now an ordinary unaltered igneous rock.

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[1] Laitakari, *op. cit.*

[2] *Op. cit.*, p. 36.

[3] P. Eskola, "On the Igneous Rocks of Sviatoy Noss in Transbaikalia," *Översikt av Finska Vet.-Soc. Förhandlingar*, Vol. LXII, A, No. 1 (1921).

On the island of Gurskö, on the west coast of Norway,[1] the writer studied a large mass of crystalline limestone surrounded by an intrusive gneiss. At the boundary of the limestone there occurs a zone in the gneiss consisting of a banded clinopyroxene-oligoclase rock. This rock undoubtedly has obtained some of its lime by assimilation of the limestone, and its characters are, in so far as regards the structure and probable mode of intrusion and consolidation during vehement movements, closely similar to those of the western Massachusetts rocks.

In all cases mentioned, acid magmas have been enriched in lime derived from limestones and have crystallized as such without any considerable change of composition through differentiation. We shall not discuss here at all those processes by which alkaline rocks are supposed to form from igneous magmas which have assimilated carbonates.[2]

Diopside pegmatites in limestone regions.—While rocks, in occurrence and origin similar to the diopside gneisses described, are uncommon, there are in most limestone areas cut by granites, very numerous dikes of pegmatite containing diopside, titanite, and other lime-bearing minerals. Such pegmatites occur so commonly in the western Massachusetts area[3] and elsewhere, that we do not need to give any further examples. The large quantity of titanite present in many of these dikes is remarkable.

The writer's field evidence from southern Finland goes to prove that the assimilation of lime has taken place within the pegmatite fissures themselves and not in the granitic parent magmas of the pegmatite. This is well illustrated by the frequently observed feature that a pegmatite, cutting through limestone and other rocks as well, has developed much diopside and titanite only while intersecting the limestone, but is an ordinary mica pegmatite outside of the limestone.[4]

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[1] P. Eskola, "On the Eclogites of Norway," *Vid. selsk. Skri. Mat.-naturv. Kl. I*, No. 8 (1922), p. 24.

[2] As the writer has suggested, the Sviatoy Noss rocks show an incipient stage of development toward "alkalinity."

[3] B. K. Emerson, *U.S. Geol. Surv., Bull. 597*, p. 19.

[4] Cf. A. Laitakari, *op. cit.*, p. 7.

The pegmatites, like other igneous rocks, show a varying behavior toward the limestones: The writer has seen, in several limestone areas, swarms of pegmatite dikes some of which carry clinopyroxene and titanite whereas others do not and could find no differences to which this might be ascribed.

The common occurrence of phenomena of assimilation in pegmatites interests us because it proves decisively that this process does not require any high temperatures. The pegmatites crystallize out from residual solutions which still exist in liquid form after the main igneous bodies have become solid. The common occurrence of β-quartz as well as α-quartz proves that the temperature has frequently been below their transformation point at 575° during the crystallization of pegmatites.

Now, what has been the temperature of consolidation of the diopside-bearing varieties of the Becket gneiss? If we could estimate this, we would know that the assimilation took place at slightly higher temperatures than that of the beginning of crystallization. This must have happened between the three-phase points quartz-calcite-wollastonite and quartz-dolomite-diopside invariant under the existing pressure. The higher of these points apparently lies below the inversion-point α-quartz-tridymite, but at present we cannot state it more closely.

The other minerals of the gneiss indicate that the temperature had decreased very much before crystallization was complete. The rock contains epidote as individual large grains associated with albite, the epidote probably not being entirely of secondary origin. The potash feldspar does not contain any threads of albite (perthite), a fact that might indicate that the temperature was so low when the microcline crystallized that no considerable amount of albite could be taken into solid solution to separate later and form perthite. Only the lowest-temperature pegmatites contain such homogeneous potash feldspar.

Turning finally to the question why limestone is assimilated in some cases and in others not at all, it seems that this may be largely dependent upon mechanical conditions. Assimilation is promoted, if the intrusion is connected with folding and the intrusive magmas are agitated and mixed with the crushed materials from the country-rock. This is in accordance with the experience that assimilation usually occurs where the intrusive rock shows banded structure and a high degree of protoclastic crushing and shearing, while it does not occur in masses which have been intruded and crystallized under quieter conditions and have come in contact with the country-rock along smooth surfaces only.

It does not seem, however, that the whole question can be covered by this explanation only. There are no doubt differences in the physicochemical conditions, in the concentration of volatile compounds, etc., which cause assimilation to occur in one case and not in another. Such relations may be understood better as soon as more experimental evidence has been gathered about the solubility of carbonates in magmas.

SUMMARY

Within the area of the igneous Becket granite gneiss in western Massachusetts there occur several tilted up layers of crystalline limestone, called Coles Brook limestone, older than the gneiss and metamorphosed by its contact influence. In the vicinity of the limestone the gneiss contains considerable quantities of lime-bearing silicates, especially of clinopyroxene (diopside-hedenbergite) and titanite, apparently the result of assimilation of limestone by the gneiss magma.

The gneiss is markedly banded, with alternating darker and lighter bands. It was found, by determining the refractive indices of the chief mafic minerals, biotite, clino-amphibole, and clinopyroxene, that the amount of their magnesia compounds in proportion to their ferrous compounds increases with the total quantity of the mafic constituents. At the same time the amount of anorthite in the plagioclase increases. Thus the dark bands behave like the earliest separated rocks in a differentiation series. Some differentiation by crystallization really seems to have taken place after the assimilation. In certain places, however, and especially at the immediate contacts against the limestone, the actual composition of the gneiss appears to be a direct result of assimilation and no correspondence between Fe:Mg ratio and "basicity" exists.—The distribution of magnesia and ferrous oxide among the different mafic minerals was found to show a certain regularity, the mica always being richest and the clinopyroxene lowest in the iron compound. The variation of the "Fe-quotient" is believed to offer an important characteristic of crystalline rocks, though at present little understood.

When silica-bearing limestones are subjected to metamorphism there occur reactions between the carbonates and silica, and silicates of lime and magnesia are formed. The temperature of reaction varies with pressure and is different for different minerals formed, as pointed out by V. M. Goldschmidt. The writer's earlier investigations have established that, among the common accessory silicates in limestones, wollastonite requires the highest temperatures to form, and diopside and tremolite, successively lower. At still lower temperatures silica, in the form of quartz, remains uncombined. Thus we may distinguish the following types of metamorphic limestone: wollastonite limestone, diopside limestone, tremolite limestone, and quartz limestone. These types may be used, under certain conditions, as a geologic thermometer, and it is hoped that the equilibrium curves of the different silicates with the carbonates may soon be determined experimentally.

The limestones of western Massachusetts were found to represent all the above-named types excepting the wollastonite limestone. Their mode of occurrence harmonizes with the writer's earlier experience, diopside limestone occurring at the immediate contacts of the gneiss and tremolite limestone and quartz limestone successively farther away.

A review of the writer's experience from limestone-bearing regions where intrusive granites occur seems to prove that such phenomena of assimilation of limestone as those observed in western Massachusetts are not at all of regular occurrence. Preferably they seem to occur in those regions where gneiss magmas have been intruded in connection with mountain folding, thus being dependent on the mechanical conditions in all probability. It appears, also, that assimilation does not require very high temperatures, being a very common phenomenon in granite pegmatite cutting limestones.